

IMPROVEMENTS IN PARTICULATE CONTROL

- 5 The invention concerns improvements in emissions control, especially from internal combustion engines such as diesel and other lean-burn engines.

Lean-burn engines present problems in that it is difficult to reduce NO_x emissions in the presence of oxygen. Compression ignition ("diesel") engines and some types of
10 gasoline engines emit combustible particulate ('soot'). Although engine design, fuelling strategies and devices such as exhaust gas recirculation can decrease engine-out, NO_x levels, it remains difficult to decrease both NO_x and soot to below modern limits, such as are expected to be prescribed in European Stage IV regulations.

- 15 The difficulty appears to be greater for low exhaust gas temperatures, for example resulting from engine design such as light duty turbo-charged direct injection diesel engines, especially if fitted with EGR, or from light duty generally.

However, there are a great many naturally aspirated diesel engines used throughout
20 the world in vehicles, maritime craft and in stationary power sources. Although many modern engine designs utilise turbo-charging, there is a huge population of naturally aspirated engines, and this will be the case for the foreseeable future. Also, it is to be noted that in some countries, including particularly Japan, the performance enhancements from turbo-charging are not adjudged to be worthwhile, and indeed for
25 some markets, turbo-chargers are removed from modern engines during truck or bus building or re-building. All diesel engines generate soot, but the soot from naturally aspirated engines is "wet" soot, that is it carries a considerable proportion of hydrocarbons absorbed into the particles. There are currently health concerns about the types of hydrocarbons absorbed on the soot. Although the present invention in another
30 aspect has particular application to naturally aspirated diesel (compression ignition) engines, it may also find application in other engine designs which generate such particulates.

- One particularly effective treatment for diesel exhaust is that marketed by
35 Johnson Matthey PLC as the "Continuously Regenerating Trap" ("CRT" -RTM). In the

CRT system as disclosed in EP-A-0341832 an oxidation catalyst converts NO in the exhaust to NO₂, the gas enriched with NO₂ is passed into a filter for the soot and the NO₂ causes facile combustion of the soot, thus continuously regenerating the filter and preventing blocking. The CRT is especially suited to so-called heavy-duty diesel engines as used in buses and larger trucks, where exhaust gas temperatures are generally relatively high.

In the case of turbo-charged direct injection engines used in light duty applications such as cars and light trucks, the exhaust gases are relatively cool, which with other factors makes the CRT system rather less effective than with heavy duty engines.

The invention provides a process of treating internal combustion engine exhaust gas containing O₂, NO_x, unburnt hydrocarbon ("HC"), CO and soot, comprising:

- i. oxidising a substantial part of the HC, with possibly some oxidation of NO to NO₂;
- ii. treating the product of step i to oxidise NO to NO₂;
- iii. collecting soot; and
- iv. combusting the collected soot by reaction with the NO₂ and possibly any O₂ left over after steps i and ii.

The invention also provides a system for treating such internal combustion engine exhaust gas, comprising:

a first catalyst to receive engine exhaust gas and effective to promote oxidation of *inter alia* HC therein;

a second catalyst receiving the product of the first catalyst and effective to promote oxidation of NO to NO₂;

a filter effective to collect soot and retain it until combusted by said NO₂ and possibly any O₂ left over after the first and second catalyst.

Since the gas contains soot, the first and second catalysts are suitably supported on a structure permitting passage of fine solid particles. The structure preferably provides through passages, for example in a honeycomb having at least 50, possibly more, the range 100-900 cells/inch² being generally preferred, more preferably 100 to 400 cells/in².

The honeycomb may be composed structurally of ceramic or metal. Such ceramic may be for example alumina, silica, titania, zirconia or combinations such as example cordierite or silicon carbide. Such metal may be for example a refractory steel for example
5 Fecralloy. Such metal may make it practicable to provide more passages per square inch, eg up to 1200. Alternative monolithic supports are available, and it is intended to include static fluid mixers and the like, as required and subject to routine testing.

The support structure carries a coating ('washcoat') of high-surface support
10 material for catalytically active components. For the first catalyst the coating and these components are chosen so that it is effective to remove substantially all the HC. (It will normally also effect oxidation of CO to CO₂ and, to some extent, of NO to NO₂). We believe, although we do not wish to be confined to such belief, that removing gaseous HC before oxidising NO to NO₂ removes species inhibiting such NO oxidation.
15 Although part of the NO may be converted to NO₂ over the first catalyst, unconverted NO is more effectively converted over the second catalyst. In the second embodiment of the present invention, HC absorbed on "wet" soot is combusted over the first catalyst.

An effect of the first catalyst can be to increase the temperature at the inlet of the
20 second catalyst to a level at which the velocity of NO to NO₂ conversion is sufficient to provide more NO₂: the subsequent soot combustion reactions are also then faster. The resulting temperature should not of course be in a range at which NO₂ formation is equilibrium limited.

In the first embodiment of the invention, it is desirable to obtain an adequate
25 reaction rate over the first catalyst for the reaction of gaseous HC; its inlet temperature is preferably maximised by disposing that catalyst as close as possible to the engine outlet. Thus it is typically mounted in the cylinder block region, for example on the exhaust gas manifold before or after a turbo-charger if used. To attain or increase such temperature
30 rise, additional fuel eg diesel fuel, may be dosed upstream of the first catalyst and oxidised thereon. Alternatively or additionally, the engine inlet fuel injection profile may be adjusted to increase the HC, or more conveniently the CO, content of the raw exhaust gas. Preferably such measures to increase gas temperature continue to provide a lean gas composition. Enrichment with HC and/or CO may be continuous or, preferably,

intermittent and initiated upon the detection of appropriate exhaust gas conditions. However attained, the temperature at the outlet of the first catalyst stage is preferably at least 200°, and eg up to 500°C.

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Preferably the first catalyst has a very low light-off temperature for both the CO and HC oxidation reactions. This is an additional benefit during parts of the engine operating cycle in which exhaust gas temperatures are temporarily low, eg during idle.

10 In the second embodiment, the first catalyst contains a component capable of oxidising hydrocarbons of the type absorbed on wet soot. Suitable forms of ceria are particularly indicated, and such catalysts may comprise other components, as well as preferably one or more platinum group metal catalyst dispersed on an oxide support, which in turn is desirably carried on a monolithic catalyst support.

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A particularly preferred first catalyst for the second embodiment comprises platinum dispersed on ceria, or on a metal oxide washcoat which incorporates ceria. The platinum loading may be up to 200g/cuft. Other catalytic or promoting elements may also be present. The ceria may be present as a washcoat over a platinum-catalysed
20 alumina or over another catalyst.

Whereas the second catalyst may have the same composition as the first, it is suitably designed to be more effective for the NO to NO₂ reaction, and the temperature and/or space velocity, for example, may be different as between the two catalysts. Thus
25 the conditions for the HC oxidation and NO oxidation may be independently optimised. The temperature in the second catalytic step is preferably in the range 150 to 350°C. (Since oxidation of NO is not strongly exothermic, there is little difference between inlet and outlet temperatures).

30 In the catalysts the active material comprises generally a platinum group metal ("PGM"), especially platinum and/or palladium, optionally with others eg rhodium. The exact composition of the catalyst is chosen to suit local requirements. Desirably they have relatively high (eg 10-150 g/ft³) loadings of platinum, and optionally may have other catalyst components such as rhodium or palladium or catalyst promoter

compounds.

The soot filter may be any capable of collecting the soot without causing excessive back-pressure. Its detailed specification is chosen according to the particular engine characteristics and the regulations to be met. It may be a ceramic wall flow filter, a ceramic foam filter, ceramic fibre filter, sintered metal or wire mesh filter of any suitable type. It may provide for removal of 50 to 100%, preferably at least 60%, more preferably 85%, or greater, of the measured soot in the exhaust gas. There may be a fail-safe bypass or a two-stage filter to cater for a situation where the filter would otherwise be blinded or blocked under certain engine operating conditions. If desired, the filter may be catalysed or part-catalysed to assist combustion. A variety of catalysts are known to be suitable, and these include one or more oxides of vanadium, cerium, and mixed Cs/La/V oxide and supported PGMs. The invention includes the possibility of initiating combustion of the soot if required, for example if the engine operating conditions are such that considerable soot is being/has been generated but the gas temperatures are rather too low for significant combustion; for example initiation may be by providing electric heating of a portion of the filter. The soot is generally carbon and/or heavy hydrocarbons, and is converted to carbon oxides and steam.

It is desirable to use low sulphur-content diesel fuel, suitably below 50ppms, and more preferably "ULSD" or ultra-low sulphur diesel of 10ppms or lower.

The invention provides also an engine in combination with a system as herein defined and a process of operating such an engine.

In this combination, in the first embodiment the first catalyst may be disposed close to the source of exhaust gas, to obtain a maximum convenient operating temperature and reaction rate therein. The outlet gas from that catalyst may undergo cooling, for example in a non-insulated or finned pipe, before entering the second catalyst.

In the combination of the second embodiment, the first catalyst is suitably disposed close to, desirably in, the same housing or "can", as the second catalyst and the filter. It is possible to contemplate a single catalyst monolith or "brick", one end of which carries the first catalyst, and the other end of which carries the second

catalyst, providing appropriate catalyst design and catalyst manufacturing technology is used, and providing that gas flow rates and space velocities are suitable.

5 The combination may include expedients such as EGR.

 The combination may include sensors for at least one of: fuel composition; air/fuel ratio at engine inlet; exhaust gas compositions at critical stages; pressure drop. If engine inlet adjustment and/or fuel injection is used, then a temperature sensor after the
10 first catalyst, and possibly before that catalyst and/or at the inlet of the NO oxidation catalyst are preferably provided. The control system may include also indicator means informing the engine operator, computer means effective to evaluate the data from the sensor(s), and control linkages effective to adjust the engine to desired operating conditions taking account of eg start-up, varying load and chance fluctuations, and to
15 inject fuel into the exhaust gas if desired.

 Preferably the engine is a diesel engine, although other engines, including direct injection gasoline engines, may also benefit from the invention. The engine may be the motive power for a vehicle, or may be a stationary power source or auxiliary power
20 source. Most usefully the first embodiment is applied to a light duty engine as defined above, especially powering a passenger car or light truck or van. Generally "light" means less than 3500kg unladen weight. This may typically correspond to a cylinder capacity up to 6.0 litres and a power output up to 300 KW. The invention is potentially of value for engine for other duties. Desirably, the second embodiment is applied to "heavy duty
25 diesel" engines.

 It is believed, although we do not wish to be restricted by any theory, that the system and process of preferred embodiments of the invention, whilst permitting combustion of hydrocarbons in the first zone, generates sufficient NO₂ in the second
30 zone to provide the right balance of NO₂ to carbon for combustion in the particular trap, under typical diesel operating conditions.

 If desired, the present invention may be combined with additional means to reduce NO_x in the gases leaving the system of the invention, which may include one or

both of NO_x reduction catalysts, including catalysts of the three-way type or systems incorporating reductant addition and a suitable catalyst, and a regenerable absorber. Such means are generally known.

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The first embodiment of the invention is illustrated with reference to the accompanying drawings, in which: figure 1 is a schematic drawing of a system according to the invention; figure 2 is a graph comparing the conversions of NO to NO₂ in the presence of HC (prior art) and absence of HC (invention).

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Referring to figure 1, a light-duty turbo-charged direct-injection diesel engine (not shown) discharges its exhaust, containing *inter alia* HC and soot, into a system comprising reactors 10 and 12, connected together for gas flow at region 14. Region 14 is shown by pecked lines to indicate that the connection may be short or may be relatively long, for example with reactor 10 at the engine outlet and reactor 12 under the vehicle body. Such a long connection may itself provide cooling or may include a finned region. Reactor 10 optionally includes at its inlet 16 the sparging spray injector 18. It essentially includes bed 20, of catalyst primarily for oxidation of HC and CO, the HC content of the gas entering bed 20 being HC exhausted by the engine, possibly augmented by HC injected at 18. Control means (not shown) responsive to the temperature of the gas leaving bed 20 regulates engine inlet conditions and HC injection at 18, to keep the temperature of bed 20 high enough for sufficiently rapid HC oxidation.

Reactor 12 contains at its inlet the bed 22 of catalyst primarily for oxidation of NO to NO₂. The gas leaving bed 22, enriched in NO₂, passes into soot filter 24, where soot is trapped and oxidised by reaction with the NO₂ and O₂. Beds 22 and 24 constitute a "CRT" system. The gas, now substantially soot-free, may pass out to atmosphere if air quality regulations permit. Optionally the system may include, in the same reactor or possibly in a separate one, bed 26, charged with NO_x absorption material, possibly with an injector (not shown) for reductant or ammonia between 24 and 26, and possibly with a catalyst for reduction of NO_x to N₂.

Each bed in the system is in the form of a ceramic honeycomb, with (except filter 24) an alumina washcoat carrying active material.

EXAMPLE 1

A synthetic exhaust gas of the following composition v/v was used:

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CO ₂	4.5 %
H ₂ O	4.5 %
O ₂	12.0 %
CO	200 ppm
NO	400 ppm
C ₃ H ₆	0 or 400ppm or 800ppm
N ₂	balance.

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This was passed over a 1% w/w platinum on gamma alumina catalyst in particle form in a laboratory reactor at temperatures between 150°C and 500°C. This reactor is known to represent a typical exhaust catalyst consisting of platinum on an alumina washcoat on a honeycomb. The compositions of the outlet gas are shown in figure 2.

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The plots for gas containing 400ppm and 800ppm HC (propylene) show there is very little conversion below about 200°C. However, in the absence of hydrocarbon (as removed in bed 20), already there is 20% conversion at 150°C and 85% conversion at 200°C. It is evident that once the HC (represented by C₃H₆) has been removed in the first oxidation step the oxidation of NO to NO₂ can take place more completely, affording more NO₂ for the combustion of particulate in the subsequent step of CRT. Bearing in mind the cool exhaust gas temperatures met with in modern light duty diesel engine designs, the significantly improved conversion at temperatures below 200°C resulting from the removal of gaseous HC, is particularly useful.

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EXAMPLE 2

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The exhaust of a 4 cylinder turbo-charged direct injection Diesel engine of 2.5 litre capacity with EGR and operated at an air-fuel weight ratio of about 30 was fed to the first of 2 catalytic stages of a system as shown in fig 1 of the drawings. The inlet exhaust gas composition v/v was:

	CO ₂	5.0%
	H ₂ O	4.9%
	O ₂	13.0%
5	CO	800 ppm
	NO	100 ppm
	N ₂	balance

Catalysts 20 and 22 comprised platinum group metal supported on an alumina-containing washcoat on a 400 cpsi cordierite honeycomb. Catalyst 20 was mounted just outside the engine exhaust manifold after the turbo-charger; catalyst 22 was 1.0m downstream in an underfloor position. For some runs this was adjusted by injection of Diesel fuel using sparger 18, giving a lower but still lean air/fuel ratio. Comparative runs were carried out using at 20 another sample of the same washcoated honeycomb but without catalytic material. Runs were made at a range of load levels, giving temperatures in the range of 225° to 325°C, measured at 22 inlet. The outlet gas was analysed for NO, and total NO_x and NO₂ calculated by difference. The table shows the concentration of NO and NO₂ at representative temperatures.

Temp°C		225°		275°		325°	
N oxide		NO	NO ₂	NO	NO ₂	NO	NO ₂
No Fuel	Cat	82	5	78	36	68	63
	Non-cat	96	1	80	18	70	54
+ Fuel	Cat	71	3	73	33	84	42
	Non-cat	65	3	78	26	88	36

It is evident that, except at the lowest temperature in presence of added fuel, the use of the first stage catalyst gives a significantly higher concentration of NO₂, thus providing for more efficient combustion of collected soot on filter 22.

The second embodiment of the invention is now exemplified below. A variety of

typical oxide catalyst supports, in particulate form, were impregnated with Pt at the wt% shown in Table 1, using aqueous solution of Pt salts, by the incipient wetness technique.

The powdered samples were dried in air at 90°C. All samples were then calcined at 500°C for 3 hours in air.

The samples were impregnated with standard commercial diesel engine lubricating oil at 10wt% per sample, and physically mixed to absorb the oil. Thermo-Gravimetric Analysis and Differential Thermal Analysis was performed on approx 40 mg samples using a STA 1500 machine using an air atmosphere, at a ramp rate of 10°C/min.

The temperature of onset of combustion was determined, and the area under the DTA peak (expressed on a time basis, and normalised for sample weight) gives a relative measure of the oil combusted versus oil volatilisation. A TGA/DTA plot of a sample of the lubrication oil showed that volatilisation occurred between ca 240 and 400°C, and that combustion occurred above ca. 400°C. The results for ceria and γ -alumina are shown below in Table 1.

Table 1

Exp	Sample	Pt-loading (Wt%)	DTA Onset Temp (°C)	DTA Peak Area (μ V-S/mg sample)
1	γ -alumina	0.0	226	1098
2	γ -alumina	0.25	209	1108
3	ceria	0.0	134	2104
4	ceria	0.009	138	2165
5	ceria	0.0375	140	2125
6	ceria	0.25	132	2361

It can be seen that both samples of γ -alumina have a relatively high DTA onset temperature, but all samples of ceria show a very significant reduction, into the range of temperatures commonly met with in diesel exhaust gases. All the ceria-based tests illustrate significant combustion of the hydrocarbon oil at low temperatures.

Additional tests were carried out in essentially the same manner, but using mixtures of ceria and platinum catalysed γ -alumina, with one or both of the ceria and alumina impregnated with 10 wt% of oil. The results are shown in Table 2 below:

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Table 2

No.	Sample	Pt(Al_2O_3) Loading (wt%)	DTA Onset Temp ($^{\circ}\text{C}$)	DTA Peak Area
10				
1	Ceria ^{OIL} /alumina	0.25	147	1182
2	Ceria/alumina ^{OIL}	0.25	159	1147
3	Ceria ^{OIL} /alumina ^{OIL}	0.25	156	1355
4	(ceria/alumina) ^{OIL}	0.25	148	1915

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The beneficial effect of the presence of ceria can be seen in all samples.

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